DEVICE FAILURE ANALYSIS BY SCANNING ELECTRON MICROSCOPY

by

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I. Introduction

Scanning electron microscopy is already contributing to semiconductor device manufacture particularly in regard to failure analysis[1,...6]. Here the term failure analysis is taken to include all aspects of failure including faults in starting materials and fabrication processes and the inability of the device to stay within specification during running and-or storage. However, the application of this technique to failure analysis (and to electronic materials work in general) is very inefficient at present because the present generation of commercial scanning electron microscopes have not been designed for this type of work. Device engineers require different facilities in an SEM compared to workers who are concerned solely with the examination of surface topography. Present day SEM's have been designed with the latter workers almost solely in mind and the needs of device engineers have yet to be met. As a result those scanning electron microscopes which are employed in device engineering environments, in general, are suffering one of two fates, either they are used unmodified with a minimum of staff and as a result can only do a fraction of the work that the technique can, in principle, carry out. Or they are relatively heavily modified or supplemented. In this case the potential of the method is more fully exploited but only at the cost of additional s. .nours and ancillary equipment. In either case manage-ment can, initially, be disappointed at the significance of the results

obtained. It seems important therefore to establish as far as possible the future role of the SEM in this field. In particular it is important to establish the present limitations of the method as imposed by the availability of hardware, the more fundamental limits arising from the physical mechanisms on which the method is based, and to establish a specification for an SEM designed specifically for the semiconductor industry. This paper was written to clarify these points and to report more widely than hitherto the experience gained by using a heavily supplemented and modified commercial SEM.

It is assumed that the basic ideas behind this application are understood from the available literature [7,8]. However, Figure 1 shows the basic physical interactions involved while Figure 2 shows the scope of the application to this and related topics. To conserve space we have limited the discussion solely to device applications and we have further reduced the scope by omitting any consideration of device fabrication by the use of electron beams [9,10]. The paper is divided into the following main sections:

(1) An initial discussion of the needs of device engineers and the ways in which these differ from the requirements of workers in other disciplines.

(2) An illustration of the way in which these needs can be met by supplementary existing microscopes. This section is sufficiently detailed to act as a guide line for the establishment of similar facilities.

(3) An assessment of the role to be played by the SEM in the device field and its relation to other methods including alternative approaches using scanning electron beams.

(4) A brief synopsis of some current research aimed at extending the technique both by the incorporation of further instrumentation and by seeking to remove some of the more fundamental limitations.

(5) A working specification for an SEM designed specifically for the semiconductor industry.

2. The facilities required for device diagnostic work

2(a) Resolution

Most (i.e. upwards of 80%) of SEM studies of both discrete and microcircuit devices is done at magnifications of x 1,000 and less. This statement can be easily checked by counting the relative numbers of relevant published micrographs at various magnifications. In fact the fraction is considerably higher when those micrographs taken at higher magnification are examined critically and the question asked as to what additional scientific content such micrographs contain. Therefore compared to other workers the resolution can be relaxed. In support of this contention we can stress that much of the information used in device work is limited in resolution by physical interactions between the scanning electron beam and the specimen anyway. Even

if we consider the quantitative studies that will be increasingly important in the immediate future it is unlikely that magnifications in excess of 2,500 will be justified in industrial and applied environments because of the increasing cost.

2(b) Versatile detector arrays

Device engineers need a multimode operation of the SEM. That is to say they require to utilise all possible interactions between the primary beam and the device to obtain information about the device behaviour. In particular they need to exploit (1) electron emission and reflection to obtain information about the specimen surface and voltage distribution; (2) the various beam induced currents to locate and examine junction regions, resistivity variations etc; (3) the cathodoluminescence resulting from the beam bombardment to give information about electroluminescent processes and possibly, about temperature distributions; (4) the X-ray emission (and probably the Auger electron spectrum) to examine the contaminants present, their distribution and relate these to the observed electrical faults.

2(c) The vacuum requirements

The work has to be done in a sufficiently clean vacuum so that the ambient effects, unless introduced purposely, are minimal. This requirement brings about the need for a careful consideration

of the pumping system to be employed. The underlying reason is the problem of oil contamination. This is an old problem that has plagued both transmission electron microscopy and X-ray analysis for some years[11,12]. In brief the problem is that the dynamic oil film which exists on the specimen surface at a 10^{-5} torr vacuum, when bombarded by the scanning electron beam, polymerises and forms a coherent film which charges up under the beam excitation. As a result resolution can be lost, contrast diminished or altered and the specimen rendered impervious to attack by chemical etchants[8,13].

2(d) Temperature range

There is an increasing need for a range of working temperatures. In general specimen temperatures between 100°K and 350°C are needed. The lower limit meets the needs of most studies of electroluminescent devices. A stage capable of reaching this temperature in a controlled manner requires between 5 and 10 watts of cooling and so, in addition, can be used to maintain a power transistor, for example, at room temperature when operating at a power of several watts. The upper limit allows annealing studies of passivated devices to be carried out and also accelerated life testing of selected circuits etc. This temperature range can be achieved without excessive expense or inconvenience.

2(e) Additional facilities

It is necessary to examine devices with other techniques and under external excitations. The excitations of interest include U.V., visible and infra-red radiation. It is important to be able to make macroscopic electrical measurements such as VI and CV plots while the device is in the SEM. So sufficient electrical connections are needed. It is also necessary to be able to examine devices that are unbonded. This can be done by incorporating a micromanipulator (with two probes) in the specimen stage. Such a probe is also of use in examining one device element which is remote from a bond in a complex microcircuit. Other probes such as high impedance head amplifiers and sampling heads have to be used on occasion.

2(f) Economic factors

Due account has to be taken of the very competitive nature of industrial device development. The specification has, therefore, to be 'pared down' as far as possible while retaining sufficient versatility. Account should also be taken of the very considerable instrumentation and expertize which already exists in such development laboratories. These stipulations force a modular construction on the facility, with the minimum of elaboration other than that supplied by the user himself. The outlook in this case is to be contrasted with the university and

other fundamental environments where the reliance on the service engineer is high and where the limitations of the standard SEM are often accepted because modification and extension is outside the local experience and the emphasis is on the ultimate in resolution. We shall return to this point below in section 7. For the present it is sufficient to contrast the change of emphasis and to consider ways in which these needs can be met. This question is being considered by the instrument manufacturers, but the 'reaction' time may be considerable. To provide the necessary facilities on the existing instruments on a shorter time scale is of considerable economic interest. The next section describes one approach which meets the needs of both production engineers and of research and development workers. We can now see how this facility meets the detailed requirements listed in this section.

3. A failure analysis facility based on an SEM

3(a) General

The basis of the facility is two commercial electron columns (see figure 3) obtained from the Cambridge Instrument Company. One of these columns is oil-pumped and the other is evacuated by ion-pumps. The oil pumped column is used for 'routine' inspection in which many devices have to be examined but only for a short

time. The more detailed scientific work is done in the ion pumped column in which problems of oil contamination are greatly reduced (see below). In each case the column, the associated specimen chamber and instrumentation are designed so that a wide range of specimens can be examined over a wide temperature range with many detector systems. Arrangements have been made so that specimens can be subjected to external excitations such as UV, visible and IR radiation and to ion etching. The console labelled semiconductor instrumentation houses both the instrumentation needed for the various detector systems in use and the control gear for the ion pumps and for the heating and cooling stages. The recording gear is housed in a separate, portable console. Three other portable consoles house (1) the excitation sources of interest in device work, (2) a spectrometer for examination of cathodo-luminescent spectra from electroluminescent devices etc. (3) Additional diagnostic facilities such as CV and GV plotting which can be used while the device is actually in the microscope, and additional techniques which complement the use of the SEM. Infra-red microscopy is shown as an example. Finally, we have shown

the small envisaged desk computer facility that should, and probably will be, included in this general facility.

Several general points should be stressed about this system. The intended grouping of the various elements is shown in figure 4. Some consoles remained fixed and others are moved in and out as required. The system is, in fact, in a continual state of development with component parts being added and replaced. The facility was designed in a modular fashion to take account of these changing needs. In addition to dealing with current problems we have made educated guesses as to the likely needs in the next two to three years. These guesses are based on experience in other laboratories and in our own, and represent attempts to predict which of the contrast mechanisms inherent in the SEM will be of practical application in the immediate future. Finally, it is relevant to add that commercial availability and minimum time to get into operation was, of necessity, given high priority in this work. In other words we only built those components we could not purchase. This comment is particularly true of the electron optics and specimen chamber. As a result a hybrid instrument results

which performs well but was not designed for the outset with this type of work as its main application.

It is intended that two people operate the system. One, who has experience of the technique, and the other will be the device engineer with the problem to be investigated. In this way we ensure that only relevant measurements are made and we familiarise device engineers with the method. Scientifically there is little new in this facility. But the important point to stress is the way in which the SEM and more conventional techniques are combined. With such a combination quantitative results which are not obtainable by other techniques can be obtained and a full use can be made of the available instrument time. We shall discuss the economics of this technique below. For the present it is sufficient to say that the present combination can cope with 'hurried' problems arising from troubles or uncertainities in production engineering and with more detailed and time consuming work applicable to a research or development laboratory.

We begin the more detailed description of the facility by considering the electron optics, the specimen chamber and the pumping system.

3(b) The electron columns, specimen chambers and pumping systems.

Both systems use available electron columns complete with gun, scan coils, modulation coils and aperture changer. The specimen chambers used are also commercially available. The oil pumped column needs no further description and the ion pumped column is a re-engineered version of the system described by Sulway[14, 8]. The scan and modulation coils are retained in the vacuum of the column. The only significant changes made to the column are:

(i) to replace all elastometer seals by Viton rings and (ii) to repolish, regrind or redesign all joints until the leak rate (as measured by a He leak detector) was minimial. Once this had been done the electron column was permanently pumped at 2×10^{-7} torr even with the chamber at ambient. The experience gained with this system can be summarised as follows:-

(1) The chamber is pumped by a 280 l-s ion pump directly connected to the bottom of the chamber through a flat valve. The column is pumped by a 140 l-s ion pump which is situated about 18" away from the column. Neither pump is ever "let down to air".

(2) The roughing out system consists of a rotary pump connected via stainless steel hoses and a molecular sieve to the exit ports of two

sorbtion pumps. The same pump is connected via the molecular sieve and a narrow bore tube directly to the chamber and the column. The initial pump out is done through the latter system until the pressure reaches approximately 200μ. (time taken approximately 3 minutes). This is then closed off and the sorb pumps, backed by the rotary pump, take the pressure down to approximately 10μ, (time taken between 5 and 6 minutes) when the main ion pump can be brought in. The system is ready for use at a pressure of between 10^{-6} and 10^{-5} torr within seconds.

(3) A liquid nitrogen container is connected to the chamber via a right angle valve. This system contains an inner chamberof liquid nitrogen which cools a baffle. This inner chamber and baffle is enclosed by an outer chamber of liquid nitrogen and an optically dense baffle and so the system has a cooled 'life' with one filling in excess of 48 hours. This greatly aids the ion pumps as it effectively removes the condensible vapours. The whole system, ion pumps and nitrogen 'pump' can be left unattended overnight.

(4) No loss of resolution is experienced because of the presence of ion pumps. 400Å edge resolution is obtained and this is limited

at present by building vibration. Some light is initially emitted by the pump but this is shortlived and can be dealt with[14].

(5) The chamber can be cycled 10 times in one day without pump fatigue. The pumps have a life in excess of two years without even a mild reconditioning. Filament lifes of 80 hours or more are common.

(6) The ultimate pressure in the chamber without baking is approximately 2×10^{-7} torr and is currently leak limited but is adequate for present needs.

(7) Contamination sensitive specimens can be examined for prolonged periods without evidence of contamination. Even with a very dirty specimen stage, which is the remaining source of contamination, such specimens can be examined for 10 to 50 times longer than with an oil pumped system. With a clean stage the charge delivered by the beam can be increased over a thousandfold compared to the oil-pumped system without the observations being obscured or limited by contamination. No evidence that Ti from the pumps effects the data has been observed in two years experience.

3(c) The semiconductor instrumentation console

3(c) 1. General

The main requirements to be met by this console are

(1) To provide the necessary equipment so the device can be tested in the SEM to check that the characteristics are the same or differ from those measured in the laboratory from whence it came.

(2) To provide the necessary biases and measurement gear so that the devices can be examined in the SEM under known and controlled conditions.

(3) To allow a rapid switching of say, 10 leads from a micro-circuit to various amplifiers, test instruments and bias supplies with safety and convenience.

(4) To permit the control of specimen temperature both up to approximately 400^{o}C and down to approximately 100^{o}K.

(5) To extend the capability of the standard instrument so that quantitative data relevant to device examination can be obtained.

(6) To provide the necessary control and amplification for present and future detection systems.

(7) With the recording console, to provide facilities for recording data cheaply and quickly with due consideration to calibration.

(8) To provide a basis of instrumentation so that likely techniques currently being discussed or assessed can in course be

incorporated and to provide ancillary instrumentation so that experimental 'mock ups' can be tested without difficulty.

The way in which these needs were met can be seen from figure 5 which shows the main units currently in operation. Many of these units are conventional and need no further discussion. For example, the ion-pump control units, the bake out control units and the X-Y plotter are commercially available units which are unmodified except for the bake out control unit and the X-Y recorder to which a 'back off' facility of $\pm$ 3mV to $\pm$ 120V has been added. The temperature control of the heating specimen stages is obtained by a thermocouple control unit which adds or subtracts power increments as required. The cooling specimen stages are controlled by the same technique operating against a cold flow supplied either by a miniature Joule Thomson liquifier or by a flow of liquid nitrogen. The remaining units are of more relevance.

3(c) 2. Input from stage and the matrix switch

The output from the stage is connected to a small distribution unit on the plinth near to the stage. From this distribution unit the

eight (or ten) leads go directly to the instrumentation console through individually screened leads to the matrix switch. This switch consists of a bank of ten rotary indicating switches. The numbered positions of each switch are ganged together and an output from the specimen stage is connected to each coupled position. So, for example, output number one from the stage is connected to the number one position on each of the indicating switches. The "common" switch positions are connected to a series of output sockets which can be connected to various bias supplies, to the input of the amplifiers used and to measuring circuits, or are fed to earth via various impedance chains which include both resistor and capacity elements. In this way the circuit used can, within limits, be changed just by dialling. Virtually the only safety factor needed is to turn down the bias voltages before making the dialling change. In this way, with thought, both the devices and the amplifier input stages are protected against overload.

3(c) 3. Bias supplies for specimen circuits

Experience has shown that three types of bias supply are of value. Commercial units which give, say, 0 to 60V in .1V steps with reversible polarity and overload protection are very

convenient for much work. However, they do introduce hum and the range of voltages available is not always that required. Battery supplies are probably best for detailed work. They introduce no hum, are stable and can be floated at will.

Experience has shown that the resistor chains should be capable of carrying up to 100 to 200mA if the unit is to be of full value. Finally, it is important to have slow voltage ramps available. The context in which these are used occur when the signal from one area of the device is required as a function of bias. In this case the primary beam is kept stationary and the required signal recorded as the bias is increased (then decreased) at a suitable rate. This facility is particularly useful in studying effects associated with avalanche breakdown and in examining defects associated with the SiO_2-Si interface in surface controlled devices. Commercial units are available for this work which give up to $\pm$ 10V at $\pm$ 10mA. For some applications this is inadequate and we have found it necessary to include two further stages. One is a differential voltage amplifier which, when driven by the ramp generator, gives up to $\pm$ 100V at $\pm$ 10mA. The second stage is an emitter follower section which will deliver up to $\pm$ 100V at $\pm$ 200mA under the same conditions.

3(c) 4. Other bias supplies

Relatively stable, high voltage supplies are of current use and are likely to be even more important in future. The envisaged uses include:

(a) The operation of additional photomultipliers for luminescent work.

(b) ~ › bias high voltage diodes and high resistance bulk specimens.

(c) To float the specimen back in potential towards the cathode potential. In this way the energy of the electrons impinging on the surface is reduced so that surface voltage distributions can be studied[15,16].

(d) To operate collector systems, deflection grids and lens systems etc. which are additional to those in present use. In addition a 3kV source which is capable of deliverying 10mA can be used to drive an ion source.

3(c) 5. Calibration

The basic calibration depends ultimately on the presence of a built-in DVM. In this way drifts and instability effects can be reduced to low levels because 'instantaneous calibration' can be carried out in

situ. Often it is convenient to have a second calibration system available for use when the DVM is already in use. To this end a zener cont rolled circuit delivering a known range of voltages or currents is used to calibrate the various amplifier systems used.

3(c) 6. Amplifier systems

The range of currents to be dealt with is considerable and a range of amplifiers is necessary in practice. The array used in this work is over elaborate but this is often an advantage. The basic amplifiers include

(a) A pair of general purpose amplifiers capable of measuring down to 10^{-10} amps with transfer impedances of approximately $10^{8}\Omega$. One amplifier is A.C. coupled and has a useful bandwidth of between 7Hz and 1MHz. The other amplifier is D.C. coupled with a calibrated current back-off. This amplifier can be used over a frequency range of D.C. to 20KHz. The input impedances of these amplifiers are of the order of 10 and 1,000Ω respectively. Often they are used with series resistors in the input to protect the amplifier against overload.

These amplifiers are used to examine microcircuits in the conductive mode, to obtain luminescent micrographs and to make quantitative measurements.

(b) An electrometer operational amplifier with high input impedance for high impedance voltage and low current applications. This amplifier is housed in the distribution unit near to the stage and has a specially designed input lead from the stage. This electrometer amplifier has several specific purposes which include

(1) A direct measurement of the primary beam current. The primary beam is directed into a Faraday cage which is connected to earth via the electrometer input. The output from the electrometer is used to develop a voltage across a suitable resistor housed in the console. This voltage is measured with a digital voltmeter.

(2) A low gain, high impedance amplifier with sufficient speed to form micrographs with specimen currents of between 10^{-11} and 10^{-13} amps. The position of the amplifier close to the stage minimises the input capacity. In this application the signal is fed to the matrix switch.

(3) This amplifier can be adapted to give various modes of operation including log current, current integration and differential linear current, if required.

(c) A low noise FET amplifier with a moderately high impedance (approximately $10^{7}\Omega$) for use with infra red detectors. This amplifier also finds application in measurement of electron beam induced

voltage in bulk specimens.

(d) A logarithmic amplifier for use when the range of signals observed is large. Specific applications include gain studies of microcircuit elements and studies of avalanche breakdown and current multiplication.

3(c) 7. Phase sensitive detector system

Figure 5 shows the component elements of the phase sensitive detector system used here. The applications to which this system have been put include

(a) Quantitative measurements of currents through passivating oxides.

(b) Quantitative measurements of current multiplication.

(c) Quantitative estimates of the relative efficiency of various electro- and cathodo-luminescent materials and devices.

(d) Measurements of the C-V and G-V characteristics of surface controlled devices while the devices are in the SEM. In this case the system is augmented by the necessary oscillators and balancing bridges.

(e) Initial measurements of minority carrier lifetimes and other response times.

In addition the planned applications include (a) gain studies of microcircuits etc., (b) studies of surface contamination by analysing the Auger electron emission spectrum; (c) Quantitative measurements of the two dimensional voltage distribution in both bulk and junction devices; (d) studies of dynamic systems in conjunction with sampling techniques. These examples indicate the scope of the method and are by no means exhaustive. The versatility arises because by modulating either the primary beam, the specimen bias, a collector or detector bias or an external excitation considerable ability to discriminate between the various factors which contribute to the observed contrast can be obtained. This ability, coupled with an increase in signal to noise ratio and an ability to avoid difficulties in determining the signal origin, makes this system virtually essential.

3(c) 8. Other display and measurement techniques

So far we have not discussed the ways in which the information obtained can be displaved and utilised.

Table 1 shows the commonly used methods. The first of these methods is that used to make electron micrographs. The second approach is the simplest way to obtain .....

Table 1. Signal display methods

Name	Basis of Method
Intensity modulation	Signal fed to grid of scanned CRT
Line scan	Signal fed to Y plates line time base fed to X plates
Deflection modulation	Signal and frame time base fed to Y plates, line time base fed to X plates
Comparator method	The signal is fed via a comparator circuit to the grid of a scanned CRT
Contour mapping	Signal is fed via threshold detector through counting and decoding circuits to grid of scanned CRT.

quantitative information across a single line of the specimen surface. The third method is an extension of this method in that it provides two dimensional information across the surface. This approach is limited to specimens of high symmetry and simple structure. Two dimensional information can be obtained more generally using a comparator circuit. In this case the signal is compared to a preset value and only when the two coincide within fixed limits is a pulse fed to the grid of the scanned CRT. In this way 'contours' of constant signal can be obtained. This approach suffers from what might be described as an overquantisation of the information. Two dimensional maps of the data can be obtained but they are 'black and

white' only. The 'greys' are missing. Recently[17] a contour mapping system which retains the the full pictorial impact together with sufficient quantization to be able to obtain quantitative information fairly rapidly. With the above capability very good use can be made of the available time on the SEM. Provided a modular construction is adopted such systems can be incorporated at will.

3(c) 9. Sampling techniques

An obvious limitation of the scanning electron microscope is its inability in its standard form to study dynamic events occurring faster than about once per second. If the event studied is repetitive (as opposed to 'single shot') sampling techniques can be used to 'strobe' the rapidly changing picture so that it can be photographed at varying time intervals during thecycle. Initial reports[18,19] of this technique are already available and indicate its value. The present authors use a commercially available sampling unit in which the head amplifier and probe unit has been made vacuum tight for insertion into the specimen chamber.

3(c) 10. Recording equipment

The equipment used here is standard. In addition to photography for recording micrographs we use a good quality scope for recording

line scans (and for general fault finding) and a four channel UV recorder for information up to approximately 1.5 KHz. This recorder has been extended to include a bank of four preamplifiers so that any channel can be operated by either a voltage or a current source. A strip recorder serves as an all-purpose monitor of pressure, temperature etc. An obvious extension here is the incorporation of tape storage.

4. Specimen stages

4(a) Introduction

The relaxation of the resolution requirements and the need for multi-detector systems means that the stage requirements differ for this type of work from the needs that have to be met in conventional scanning electron microscopy. This point has been considered elsewhere[20,8] but it is well to draw up a specification for a stage to meet device application needs. The main requirements can be listed as follows:

(1) The stage should lead to no degradation of resolution from that which the electron optics is capable.

(2) It should be modular in construction and capable of operating in any position (i.e. on its side or upside down).

(3) It should be leak tight in operation, bakeable as far as possible, easy to clean and capable of use in vaccua of the order of 10^{-8} to 10^{-9} torr.

(4) The detector systems used should be easily interchangable and, as far as possible, should be capable of being run concurrently.

(5) The main frame work should provide adequate movement in the required degrees of freedom and, at the same time, be capable of carrying a reasonable load when some of the degrees of freedom are sacrificed. Finally, it should be capable of accepting a series of sub-stages or 'modules' for specific purposes.

(6) The system should be capable of examining complex microcircuits with ease and convenience. This requirement imposes the need for multiway metal to glass seals to carry the necessary electrical leads. Also the system must include a series of modules so that the major microcircuit 'packages' can be clipped into the stage rapidly. The complete electrical circuits must be self contained within the stage. In this way the circuit can be mounted and tested initially outside the SEM to avoid wastage of instrument time.

(7) The stage must allow specimens to be heated and cooled. In the microcircuit applications the range required is approximately

100^{o}K to 650^{o}K. Although some materials work requires a wider temperature range.

(8) It is necessary to examine specimens that are being or have been subjected to external excitation such as UV, visible and infrared radiation, ion etching, various gaseous treatments and evaporations etc. The stage should have sufficient shielding to give a reasonable life between cleannings.

The next section outlines one method of achieving the necessary framework.

4(b) A specimen stage for device work (2) main framework.

Figure 6 shows the basic features. The structure is in stainless steel. Five degrees of freedom are introduced via bellows seals to give three linear translations of 1", complete rotation and 0 to 90^{o} tilt. The bottom of the faceplate is occupied by an interchange plate containing a selection of metal to glass seals.

The basic movements are obtained by means of a wedge and two overriding frame movements. Contained in one of these frames is the rotation-tilt, movement unit. The figure shows how two specimens (or one specimen and a Faraday cage) can be accommodated. We consider the incorporation of the substages below. A post

fitting (far left in figure 6) allows the incorporation of a secondary electron collector system of virtually any type. It should be noted that the scintillator element of a secondary electron collector is the only soft insulator included in the framework. There is sufficient space at the rear (bottom left in figure 6) to accommodate additional detectors or head amplifiers. The 1" vertical movement means that detectors can be placed above or below the specimen. Optical viewing and external excitation can be obtained from the side ports via the 'cutaway' sections shown in figure 6.

4(c) A specimen stage for device work (2) the substages or modules

The main modules in use at present include:

(1) A series of heating stages for microcircuits, discrete devices and bulk specimens.

(2) A series of cooling stages based on the 'minicooler' idea i.e. using a miniature Joule-Thomson liquifier and a high pressure gas flow.

(3) A long working distance microscope for observing the specimen either directly (or through the end of an ion source). Additional use as a chopped photoconductive flood beam is also very valuable.

(4) A holder of symmetrically placed photo-diode(s) together with balancing circuit for compositional contrast.

(5) A fibre glass light collecting system for cathodoluminescence in the visible spectrum.

(6) An R. F. ion etching source for surface physics studies associated with ma terials preparation.

(7) A special mounting so that the specimen can be floated in potential towards the gun potential.

In addition the following components are being built:

(8) A joint heating and cooling stage to cover the range $80^{o}K$ to $750^{o}K$.

(9) A heavy duty cooling stage using a liquid N_2 flow.

(10) A micromanipulator probe, which can be used to make contact with unbonded devices.

(11) A UV source and optics system for annealing studies of insulators and wideband gap semiconductors.

(12) An infra red cathodoluminescence detector system complete with two channel multipliers.

(13) Facilities for baking the stage.

(14) A detector system so that scanning transmission electron microscopy can be done with this stage.

(15) A sampling probe for dynamic studies.

Finally, a design study for an Auger electron detector system is being made for use in surface preparation work.

Figures 7 to 9 show some of the systems employed. Figure 7 shows a selection of the heating modules used. They all consist of an O. F. H. C. Cu block heated by small lengths of 'thermocoax'. The device is inserted into a push fit hole in the centre and held by two screws which also act as locating posts fixing the module to the stage movements. Such modules can be used for long periods at temperatures up to 250°C (up to 350°C with some shielding). The temperature is controlled by a Cu constantin thermocouple inserted into the block. The element resistance is approximately 1Ω and a 5A, 5V power supply is needed. There is full x, y and z movement available, but both tilt and rotation can be limited by the electrical leads to the device. However, considerable tilt and rotation are available. In this context it is of interest to recall that much microcircuit work is done with the device at right angles to the primary beam and with new detector systems or configurations, even more will be tractable in the near future. Electrical connections are made with screw on or push on leads. Solder joints are to be avoided as the fluxes used appear to contribute to the contamination problem.

The above modules can accommodate three TO18 headers, two TO5 headers, one TO3 header or experimental and bulk devices. They are not suitable for flat pack devices. In order to make modules for these devices we have adopted two approaches which are being assessed. The first method uses specially fabricated metal to glass 'seals' in which the metal pins mate with the leads from the flat pack device. The seal is then mounted on a heating element. The second approach uses a new polyimide material ('Vespel' manufactured by Dupont) which is an excellent insulator, is machinable, is a good vacuum material and can be baked at 450°C. We are fabricating heating modules for flat pack devices with this material.

Figure 8 shows cooling modules that have been used for device work. Experience has shown that three types of cooling stage are required: (a) a 'quick reaction' module which can reach a low temperature quickly which is based on the 'minicooler' idea[21], (b) a heavy duty cooler based on a liquid nitrogen gas flow and which has, relatively, considerable thermal mass and (c) a combined heating and cooling stage to give the complete range - 180°C to 350°C. Figure 8 shows experimental cooling modules based on the Joule Thomson effect. Temperature control is obtained by incorporating a small heating element. With the availability of finned tubing it is now possible

to fabricate such coolers cheaply to meet the special needs of this type of work. Such 'home made' coolers are, in general, not as efficient as those available commercially. Figure 8 also shows an experimental joint heating-cooling stage which retains most of the available degrees of freedom. Such sub-stages are easy to construct once a basic versatile set of movements is available.

Finally, figure 9 shows how the stage can be used in conjunction with external excitations.

5. Initial discussion

The preceding sections illustrate just what can be done with hybrid instrumentation in this field. By hybrid we mean systems in which ad hoc ancillary systems are added to an SEM which was designed to do only a fraction of this work. These sections also illustrate the type of effort involved in establishing this type of facility. With such a facility it is possible to extend the technique as far as the current physical understanding of the contrast mechanisms allows. We shall return to this limitation below. First we have to consider the application of this technique to commercial laboratories. In particular we have to answer the question as to how far it is necessary to take the instrumentation in the manner indicated here. To consider this question we have to make some general points. For convenience we divide the faults to be studied into two groups. The first could be

called 'production engineering' faults in which the SEM is used as a routine inspection tool. In general these are surface faults. Included in this category are such faults as:

(1) packaging and bonding problems. Misalignment of component elements, pin hole formation, 'open' windows, cracked bonds, 'porous' oxides, the retention of lubricating oils on bonds, poor alloying etc. etc.

(2) Faults in initial starting materials both before and after processing. Included here are such faults as dislocations due either to crystal growth, high diffusion concentrations, or faulty epitaxial growth, trace impurities in local concentrations, microcracks, scratches etc.

(3) Faults which develop during accelerated life testing.

The second group of faults can be called research and development faults in which a scientific explanation is sought for a device failure, such as low gain, excess noise, excess leakage, low breakdown voltage etc. Witn this classification we can indicate the scope of equipment of varying degrees of sophistication.

Most of the faults listed under packaging and bonding can be dealt using a conventional scanning electron microscope with very minimal modification. The vast majority of these faults are detailed examinations of surface topography in one form or another, which is

the purpose for which existing instruments were designed. The only addition compared to life science and other surface topography work is the need to observe the surface voltage distribution on a biassed device. Biassing facilities are readily made available so that qualitative voltage studies can be made. But such studies are strictly limited compared to the potential scope of the method. Within this limitation these problems can be tackled with a conventional oil-pumped SEM with the necessary electrical connections being made through a side-plate. With regard to materials and processing faults further complication has to be introduced. To study such faults it is necessary to make special large area devices using the processes to be exploited in commercial devices[3]. Most of the faults which are known to occur in device materials and processing lead to contrast on conductive micrographs, but it is more difficult to identify which particular microscopic fault leads to a given electrical fault. It is in this work that the problem of oil contamination first emerges as the oil film interferes with the detailed observation of the way in which localised defects affect and perturb a diffused or surface controlled junction. There are two ways in which this difficulty can be overcome, either the vacuum can be made far more hygenic or the devices can be examined hot in which the

contamination does not occur. The first of these two approaches is the more general. The second approach needs a heating stage (up to 200 to 250°C) and presupposes that the heating of the devices does not lead to complications in physical interpretation. It is our experience that this 'annealing' does in fact introduce such complications. At the very best it limits the scope of the studies that can be made particularly those involving quantitative estimates. Therefore, for full exploitation of the technique, it is best to remove the oil vapour from the system to a level at which it ceases to be a worry. This type of fault analysis needs considerable instrumentation of type outlined above.

With regard to accelerated life testing this work can be done in an oil-pumped column with a heating stage together with an ability to inject gases in small controlled amounts. (This later type of experiment is perhaps more suited to the research and development laboratory as it is better performed against a low background of residual gas (10^{-8} to 10^{-7} torr)). Finally, if quantitative scientific studies of devices are required in depth a full facility of the capability shown here is required. Research management may wish to argue that considerable economy could be made by just using equipment from other projects on a temporary basis to do a particular job on the

SEM rather than have an elaborate array 'tied down' to this job. We believe this to be false economy as it is based on a 'lowest cost' philosophy as opposed to a 'value for money' outlook. The important point to establish is that the best value for money is obtained when the electron column is in operation for as great a fraction of the working week as possible. Maintenance time on existing instruments is minimal, the pump down time is 2 minutes with oil pumps and 6 minutes with ion pumps (to 3×10^{-6} torr). If an hour has to be spent locating, checking and wiring up minor equipment the cost in lost time is considerable. We would stress this point most strongly. The experimental mock-up approach really has no place under these conditions. We also believe that economy on staff by using junior or technical as opposed to relatively experienced scientific personnel is largely imaginary. The whole facility should be designed to have a continuous flow of specimens through the system and a continuous programme of development to extend the facility. We believe that device manufacturers have to become conditioned to extending a standard SEM to a facility of this capability based on two columns or two complete instruments. This situation, we would sugges is forced upon manufacturers by the power of the method and its money and time saving property if properly exploited. We shall return to this point below. First we have to outline the more fundamental limitations of the SEM and its relation to other diagnostic techniques.

6. Limitations of scanning electron microscopy

6(a) General

With a system with the facilities outlined above most of the potential of the SEM in the failure analysis field can be exploited. The remaining limitations arise from an absence of understanding of some of the contrast mechanisms observed and from the fact that there is the possibility that examination in the SEM will alter the properties of the microcircuit under examination. We feel that the resolution of the SEM is not a limitation. We have mentioned this point in section 2. The important property of the SEM is the way in which it makes it possible to examine macroscopic, albeit small, devices, in operation at sufficient magnification for the electrical properties to be related to microscopic defects of the size of x 2,000Å or more, and to examine the underlying junctions and insulating layers by studying the various beam induced currents. If we accept this contention for the present we have just the 'irradiation damage' problem and the problems posed by physical interpretation. Consider the latter problem first.

6(b) Limitations to lack of comprehensive understanding.

This problem can take several forms, but two are the most important. One is the difficulty in obtaining a unique interpretation

of the cause of fault observed as opposed to a mere location of the fault without investigating its cause, and the second is the utilisation of the available physical interactions (the available contrast mechanism) in situations of practical, i.e. commercial importance as opposed to carefully chosen, simple cases used in more fundamental studies. We can illustrate this type of problem by considering the exploitation of the voltage contrast mechanism[22] whereby we locate and examine the surface location of p-n junctions and examine surface voltages in general. Figure 10(a) shows an emissive micrograph of a planar transistor taken with a microscope which had, immediately before, given excellent results with other devices. It can be seen here that the micrograph obtained is very poor in that it is excessively noisy. The micrograph shown in figure 10(a) was taken with no applied bias, but the identical micrograph is obtained with 12 volts across the collector-base junction. In other words the voltage contrast mechanism is inoperative. If, instead of examining the device at 20°C, we heat the device to 120°C re-examine we obtain the results shown in figures 10(b) and (c). The signal level has risen and the voltage contrast mechanism is operative. This same apparent temperature dependence of the voltage contrast mechanism is shown in figures 10(d) to (g) which also illustrate the cause. In the first two micrograph

taken at room temperature, the voltage contrast is poor and the insulator parts of the metal to glass seals are 'charging-up' under the bombardment. This effect can be in terms of the two bright rings marked A around the metal post on the seals. As the temperature is raised the conductivity of the glass increases until, at a particular temperature the insulator rings cease to 'charge up'. At this temperature (70 to 80^{o}C in this case) the quality of the micrograph improves quite suddenly and the voltage contrast increases in sensitivity.

The above examples are typical of the way in which necessary components of a structure obscure the observations made on the active elements. These examples also show the need for development effort into the application of these techniques in 'real' situations. The problem can become quite complex in the case of integrated arrays of devices. Often, in such cases, we have to examine a particular device element which is remote from the available electrical contacts. As many other elements are in the circuit studied the information we get about the suspected element is essentially 'third or fourth hand' i.e. modified by parallel circuits and series elements (see (8) for example). This indirectness is enhanced by the fact that we have to examine junctions under different depths of passivating layers. This relatively trivial

effect can complicate the interpretation particularly when we are concerned with quantitative studies.

Much can be done to overcome this problem with improved instrumentation and further research. Much current research is directed towards achieving this end, but at present it should be realised that we are trying to apply a new technique and develop it at the same time.

6(c) Limitations due to 'irradiation damage'.

The term 'irradiation damage' is used here to describe semi-permanent changes induced in the device by the electron bombardment in the SEM. These changes occur at beam voltages such that the electrons penetrate very near to the SiO_2-Si interface.[23, 24 and 25]. Two effects occur: (a) the density of charge stored in the oxide is changed. Usually it is increased in the final steady state, (b) the surface recombination velocity is increased probably by the introduction of 'fast' surface states[25]. These effects are bias dependent and are relatively well understood in well-behaved i.e. high developed materials. However, in new materials and in the establishment of new facilities the effects can be very complex particularly the transient behaviour before the attainment of a steady state is reached. At present we cannot do two things; we cannot guarantee that devices will not change in electrical properties under SEM studies, nor can we exploit

these changes fully to diagnose uniquely the initial faults in the suspect device. This last point can be made another way. A device engineer asks that this technique in conjunction with macroscopic studies tells him the underlying physical cause of the observed electrical failure. The mechanism has to be studied against the background of the observed irradiation induced changes and, if possible, the observed beam induced changes used to give information about the initial properties of the device. Leaving aside the transient effects which occur during the first few seconds of irradiation we can outline the general type of behaviour that can occur by discussing the typical data in figure 11. The doses used here are typical of fairly prolonged examination in the SEM. We have to decide if the observed changes in CV plot are

(1) due to radiation induced defects and are therefore of minor interest to the analysis of the initial properties.

(2) Due to changes in occupancy of an initial uniform distribution of states with a specific energy distribution, which, ideally, has to be determined.

(3) Due to inhomogeneities in the allowed state distribution within the oxide and-or interface across the device active area (i. e. due to patch effects.)

(4) Due to beam induced effects on the surface of the structure outside the upper metal contact of the MIS structure.

(5) Due to surface effects in the unirradiated device outside the area of the metal contact.

Usually some of these ambiguities can be removed by a suitable experimental procedure, particularly by the use of low beam voltages. In this case charge is injected into the upper half (or less) of the insulating layer and the resulting current flow through the insulating layer is studied as a function of position, bias etc. In this way conduction through the insulating layer can be studied with the minimum of damage to the interface etc. One set of observations which illustrate the way in which the SEM can eliminate some of these uncertainties is given in figure 12. Here the emphasis is on the role played by localised defects. An MIS structure is examined by means of the circuit shown with a low voltage electron beam and the beam induced current examined as a function of position and bias. As the bias is increased in a sense so as to cause inversion a number of small regions begin to give large current signals i.e. they represent regions of greater than average conductance. Examination of the magnitude of the excess conductance through such electrical 'weak spots' can be made by measuring the beam induced currents along a linescan through the defect, see figure 13. Examination of the surface shows that some of these defects are very small pinholes but others have no feature which distinguishes them from

the bulk layer. Both kinds of defect are apparent in figure 12. In this case it is apparent that patch effects are important and that the interpretation must take account of this fact. For example, the observed CV and GV curves are compounded of the uniform bulk regions and a random distribution of 2 to 4μ regions with excess leakage and probably excess localised charge.

In this case the SEM contributes to an understanding of the device properties. In other cases the SEM provides new data which needs further interpretation and so does not of its self contribute to our understanding. But, in general, the SEM complements existing techniques by locating patch effects, by studying 'fringe' effects outside the metal contact etc. and by studying conduction processes in the passivating layer. At present no satisfactory method has been foud of exploiting the irradiation effects to diagnose the initial properties of the device nor has any method been found to determine specific properties such as ionization energy and spatial location of states in which the stored charge is located. Work is going on in several laboratories[26,27] to extend the technique in this direction by careful experiments in which devices are irradiated by successive increments after the mobility, the stored energy and the surface free charge have been determined before and between each irradiation. By using this technique in conjunction with U-V and thermal annealing and with more

general SEM studies and possibly X-ray micro-analysis it is hoped to provide a useful way of studying surface controlled devices in detail.

In brief this section seeks to show that detailed SEM studies of the complexities that exist at the insulator-semiconductor interface are needed and have begun with the idea of applying them not only to 'production engineered' devices but to devices in an early state of development. Similar developmental experiments are needed to study and exploit temperature sensitive contrast that has been observed [28] at high current densities to investigate avalanche effects [29, 30], to make valid estimates of minority carrier lifetime in a wide range of situations, to try to develop a method of measuring quantitatively the localised variations in surface recombination velocity and to develop methods of studying the microscopic complexities of behaviour which occur when devices are used in hostile environments.

6(d) Relationship to other electron optical instruments

The contribution made by electron optical instruments to device analysis is greatly increased when the SEM and the microanalyser are used in conjunction [31, 32]. The normal procedure is to locate the electrical fault with the SEM. If there is no obvious physical reason for the defect such as a dislocation, crack or misplaced bond etc. or, if there is an obvious second phase present, X-ray microanalysis is used to investigate the origin of the fault still further. Additional

localised information can be obtained by using modified vidicon tubes to provide a scanning electron beam[15,17,33]. By biassing the specimen towards the gun potential the incident electrons have been low energies and so are of value in investigating surface voltage distributions. The 'interface damage' problem need not arise here. The method even in this simple form has yet to be exploited. In a more refined form, from the electron optical viewpoint, this approach goes over into electron mirror microscopy[34,35] in which the electrons are reflected away from the specimen surface without hitting it. Damage is absent and the method is very sensitive to surface steps and particularly to surface voltage changes. In the present context this approach is limited because, unlike the SEM, it does not go below the surface to interact directly with the active elements of junction devices and so only gives information about these elements somewhat indirectly. However, when developed commercially it should complement the facilities inherent in the SEM, particularly in regard to checking the effects of irradiation damage and in regard to surface voltage effects.

7. A scanning electron microscope for device work

Scanning electron microscopy is likely to take three parallel paths to full development:

(a) A high resolution, high reliability instrument for use in the life sciences and similar environments where skilled engineering personnel are at a premium and heavy reliance is placed on the service engineer.

(b) A 'routine inspection' instrument which is manufactured to a price and exploits the increased resolution and depth of focus compared to the optical microscope. This instrument will be used in control quality environments probably with moderate resolution and a rapid change of specimen.

(c) A 'micro-lab' kit for advanced experimental work. This latter idea needs some elaboration. There are many experimental situations in which phenomena of interest have to be examined in situ.

Examples that are of current interest include:

(1) The examination of ion implanted diodes in situ within a good vacuum.

(2) Weather control experiments in which the nucleation of ice crystals are the subject of interest.

(3) Crystal growth, surface evaporation, alloying, sintering and epitaxy are all phenomena which would benefit from microscopic examinations in situ.

(4) Deformation processes including creep, fatigue, tensile testing and impact loading as a function of temperature and surface condition.

(5) Device fabrication by electron beam exposure of resists.

(6) Work function and photocathode studies involving the use of Cs, Ba, BaO etc.

(7) Electron beam fabrication of precision mechanical parts where inspection has to be interposed with various fabrication steps.

(8) Irradiation studies

(9) Numerous other fields of interest include phase transformation (some stress induced), arc discharge damage, friction etc.

If a kit of electron column and suitable specimen chambers can be devised many of these experiments and otherscan be devised within this basic framework. Such a framework can be called a 'microlab'.

The question arises as to where a "device manufacturers" instrument can be fitted into the above development. It must be remembered that the availability of these instruments will be determined by the development effort necessary and by an educated guess at the market. From the manufacturers viewpoint the "inspection" instrument is the more attractive in terms of sheer numbers, and the development of 'microlabs' will probably be done first in University Departments. From the device manufacturers viewpoint an 'inspection' instrument plus modular kits of instrumentation for multimode operation will suffice. In other words a 'control inspection' instrument can be designed to meet the needs of the

device engineer as well. It is of interest to consider the specification of this instrument. We would suggest an instrument defined by the summary given in Table 2.

Table 2. Specification of SEM for device analysis

Resolution:-		2,500Å
Beam voltage:-		1 to 20kV, in switched steps with some continuous control about each step.
Detector systems:-		(a) Secondary electrons
		(b) Reflected electrons
		(c) Auger electrons+
		(d) Charge collection current
		(e) Specimen current
		(f) X-rays*
		(g) Cathodoluminescence*
Specimen stages:-	(a)	A simple framework for routine inspection work
		(1) x, y and z up to 1" movement.
		(2) Rotation $\pm$ 15°, possibly in 5° "click stops".
		(3) Tilt:- preset.
		(4) Heating and cooling 100°K to 650°K.
		(5) Entry for external excitations.

(b)* An all purpose modular 'kit' consisting of basic framework and substages, to match the specification given in section

Displays:- One visual for switched operation i. e. each detector system can be switched to do this display in turn. One for photography, again with switched operation. Camera mounting to match those on laboratory bench oscilloscopes.

Scan generator:- Must be solid state. Should have a limited range of scan rates but should have facilities for introducing external rasters. Should have enough power to drive four CRT's or it should be possible to run two such generators in synchronism.

Magnification:- 2, 5 and 10 scale from 20 to 5000.

Pumping units:- (a) oil pumps, pump down time 2 to 3 minutes.

(b) ion pumps* pump down time 10 minutes.

Pump control:- Manual; with indicator diagram as on most evaporator units; no automation.

Beam chopping:- Up to 10^6 Hz.

Electron optics:- Two lens system with many elements such as scan coils, modulation coils excluded from vacuum.

Modular construction:- Must be modular and small in overall size. Access to control points and entry of additional (customer made) control signals must be allowed for.

* optional extras

\+ See next section

8. Discussion

The above specification ignores extreme needs, but would enable most of the significant device analysis work to be done with a relatively cheap instrument which can be extended by 'in house' activity and by adding components at a later date. The Auger detector system has been included on a rather speculative basis because we believe it will be of immense value in semiconductor material processing. Opinion is by no means unanimous on this point but is divided into two schools. One school of thought, in general electron microscopists, is worried by the low efficiency of the process and the degradation of resolution that will occur because of the high currents needed. The other school of thought, in general semiconductor materials workers, is not concerned with the ultimate in resolution but is attracted by the thought of being able to detect the presence of very thin surface contaminant layers[36, 37].

One question that has not been considered in the above specification is the question of airlocks. In the semiconductor field this approach to specimen loading is more complicated than in other fields because of the question of electrical connections. In the case of oil pumped systems the need for airlocks is not sufficient to merit the expense. However, in oil free systems the need to consider the 'strains' on the vacuum system may justify the development of the necessary loading module complete with 'multiway' electrical plug-in connectors.

We have detailed the ways in which our own facility has developed and have suggested that this can be regarded as a reasonable basis for the development of other facilities. One point should be borne in mind in this context. We have used ion-pumps for our 'oil free' system and they work well. However, these may not be the best pumping system to use. We have no facts as to the relative merits of turbo-molecular and ion pumps in this context.

Finally, as we have already implied, the development of the facility described here has suffered both in cost and in elegance from the absence of modular instrument designed for this work. It is hoped that the various instrument manufacturers will meet this challenge and provide the necessary instruments rapidly.

9. Acknowledgements

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Captions to figures

Figure 1. Schematic illustration of the physical interactions exploited in the SEM. In our notation the secondary and reflected electrons are used to give 'emissive' micrographs of the surface; the conduction processes are exploited to give 'conductive' micrographs and the light emission is utilised to give 'luminescent' micrographs.

Figure 2. Block diagram indicating the application of the SEM to device and materials studies. In some cases the technique has already given significant data, in the remainder active 'pioneering' studies are being made.

Figure 3. Block diagram showing the basic components of the failure analysis facility described in the text. The desk computer facility has yet to be added.

Figure 4. Showing the positions of the components and the overall size of the facility.

Figure 5. Block diagram of the 'semiconductor' instrumentation currently in use.

Figure 6. General views of the specimen stage developed for semiconductor materials and device work.

Figure 7. Heating 'modules' or substages used with the stage shown in figure 6. (a) A module for use with experimental

devices, TO18, TO5 headers etc., the model shown is for use with a TO5 header. (b) Similar module for use with TO13 header. The heater (A) is a 'thermocoax' strip and the temperature is measured by a thermocouple at B.

Figure 8. Cooling modules for use with the stage shown in figure 6. (a) and (b) experimental miniature Joule Thomson liquifiers that are being assessed; (c) a joint heating or cooling stage based on a liquid nitrogen flow.

Figure 9. Use of the stage with various external excitations.

Figure 10. Example of experimental difficulties sometimes experienced with device work; the loss of signal due to the presence of insulating elements. (a), (b), (d) and (f) OV bias, (c), (e) and (g) 12V.

Figure 11. The effect of electron beam irradiation on MIS strucutres. This figure shows the change in CV plot after successive doses of irradiation.

Figure 12. The use of the SEM to study 'patch' effects in MIS structures. (a) to (e) show the development of weak spots in the insulator layer as the gate bias is varied. These micrographs were taken under the following conditions. 5KV, beam current = 3×10^{-9} amps and gate voltage in

(a) = - 14

(c) = - 15.7

(e) = - 18.3

(b) = - 20.0

(d) = - 21.6

(f) A surface micrograph taken at 20kV of the area outlined in (e) showing the sites of the weak spots in the enclosed area.

Figure 13. Line scans through weak spots such as those shown in figure 12, showing the excess leakage current which flows through such weak spots as a function of gate voltage.

FIGURE.1.

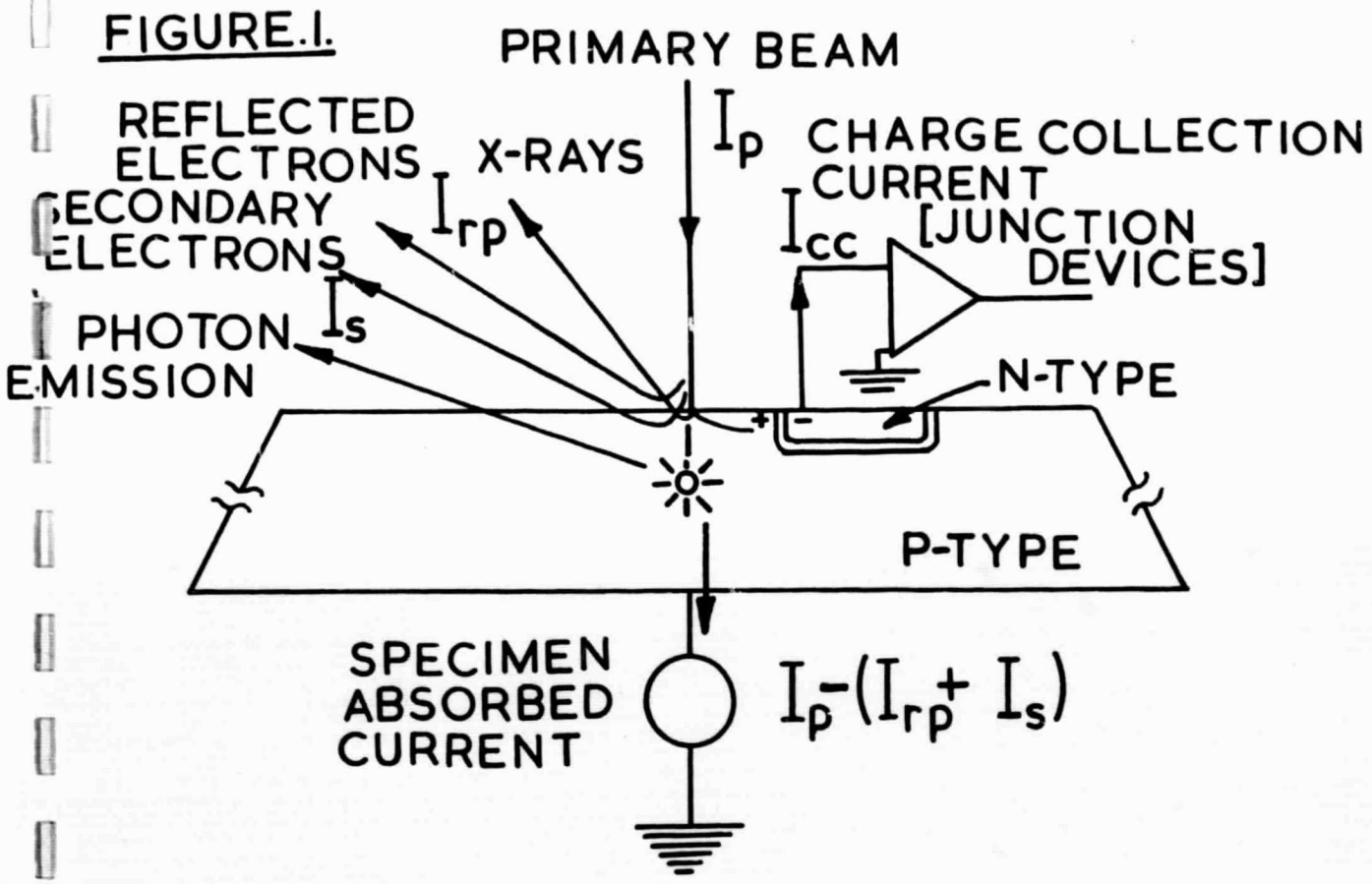


FIGURE.4.

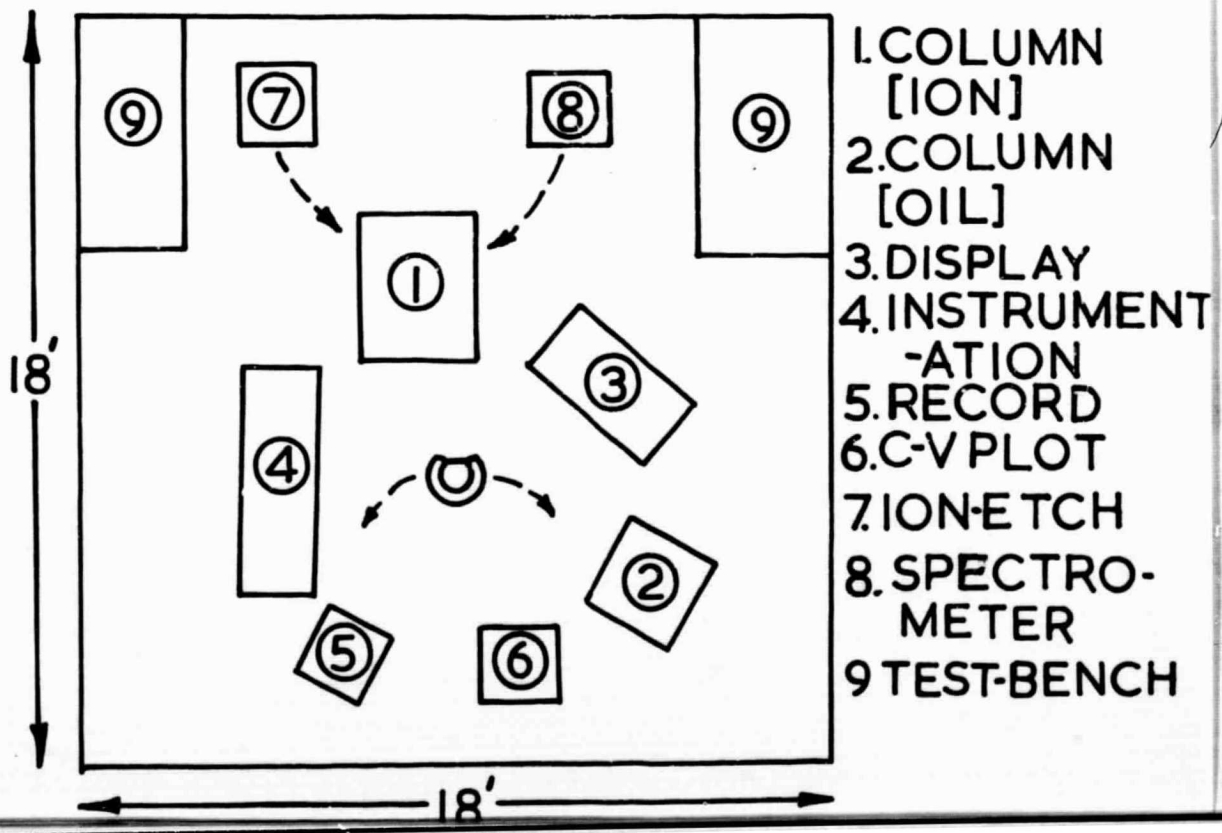


FIGURE 2

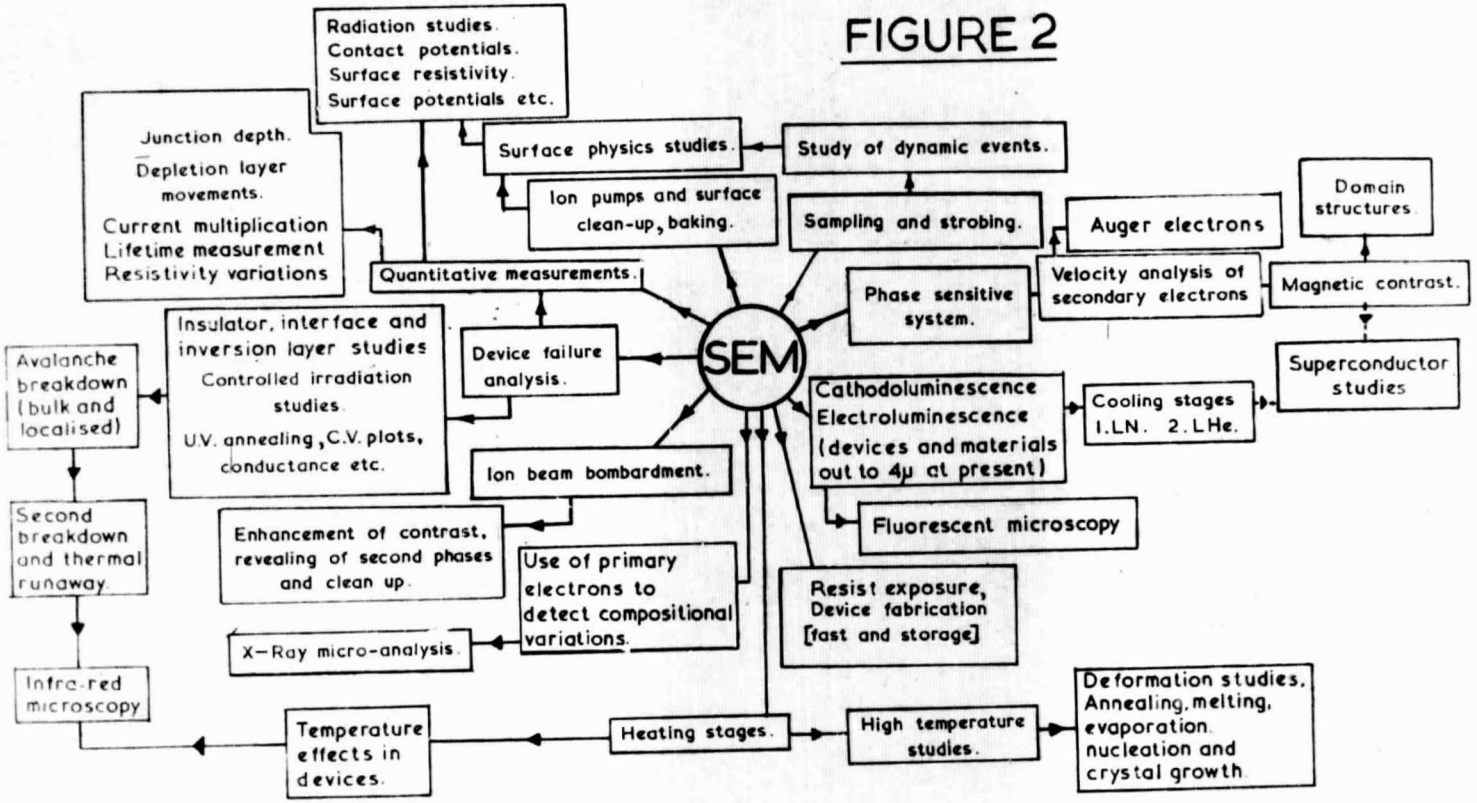


FIGURE 3

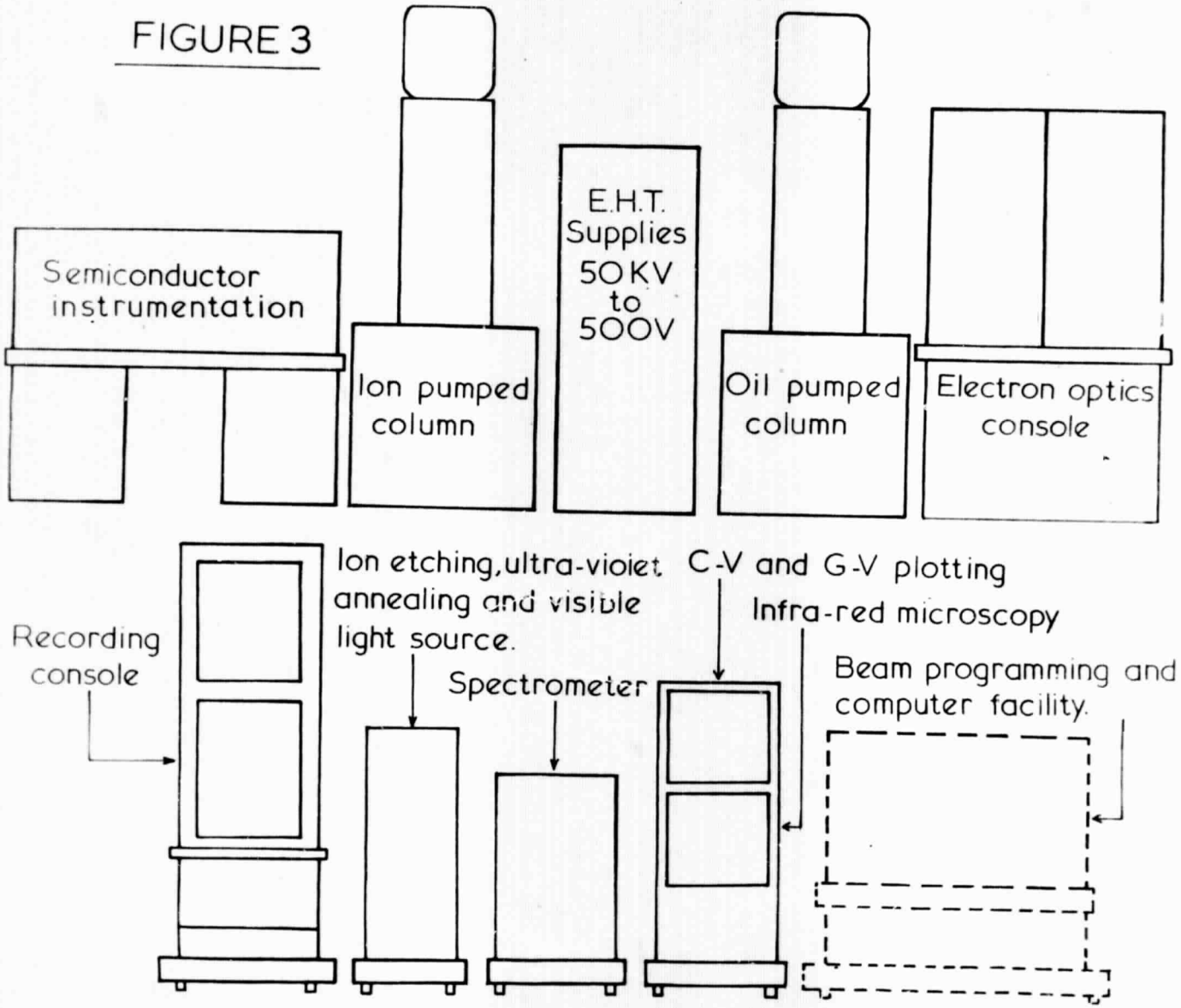

Semiconductor instrumentation
Ion pumped column
E.H.T. Supplies 50KV to 500V
Oil pumped column
Electron optics console
Recording console
Ion etching, ultra-violet annealing and visible light source.
Spectrometer
C-V and G-V plotting
Infra-red microscopy
Beam programming and computer facility.

FIGURE 5

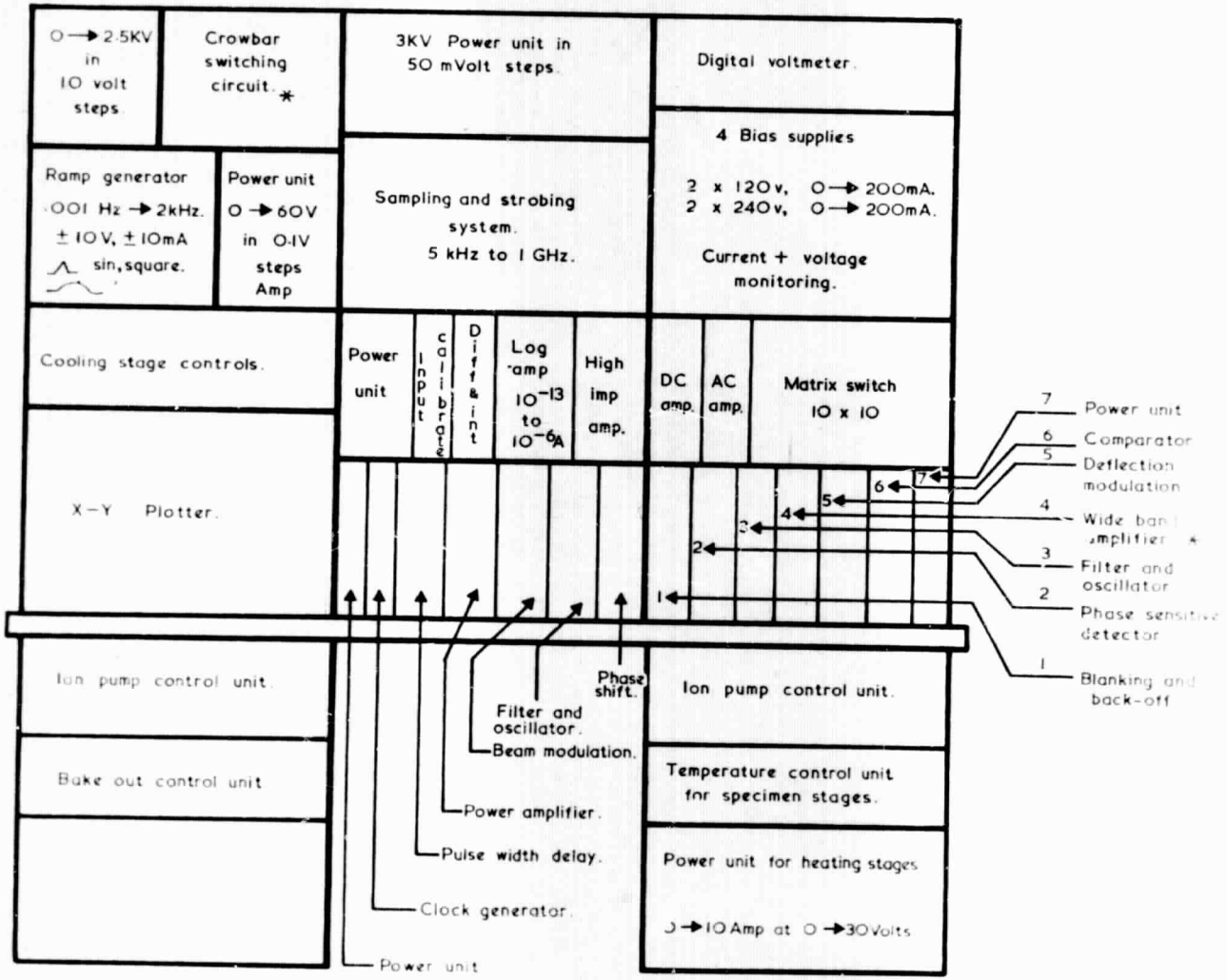
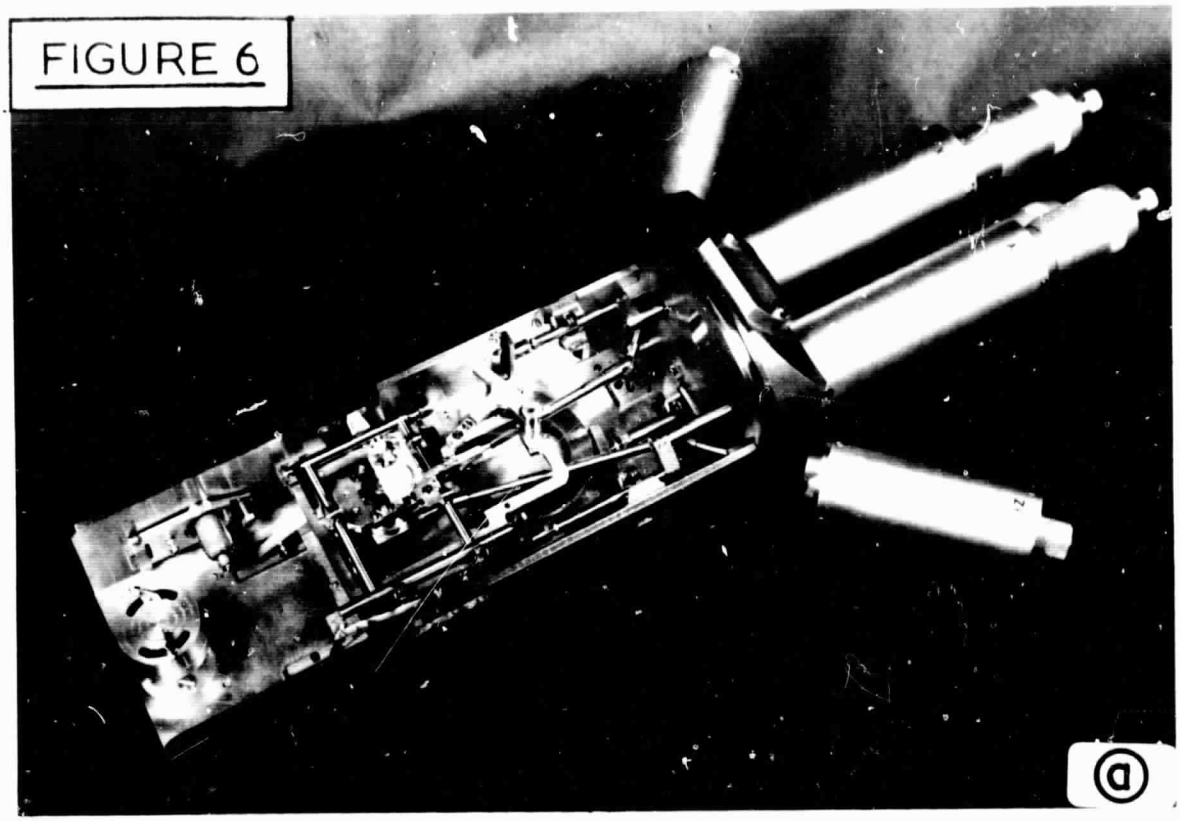

0 → 2·5KV in 10 volt steps.
Crowbar switching circuit. *
3KV Power unit in 50 mVolt steps.
Digital voltmeter.
Ramp generator .001 Hz → 2kHz. ± 10V, ± 10mA sin, square.
Power unit 0 → 60V in 0·1V steps Amp
Sampling and strobing system. 5 kHz to 1 GHz.
4 Bias supplies
2 x 120v, 0 → 200mA.
2 x 240v, 0 → 200mA.
Current + voltage monitoring.
Cooling stage controls.
Power unit
Input calibrate
Diff & int
Log amp 10^{-13} to 10^{-6}A
High imp amp.
DC amp.
AC amp.
Matrix switch 10 x 10
X–Y Plotter.
7 Power unit
6 Comparator
5 Deflection modulation
4 Wide band amplifier *
3 Filter and oscillator
2 Phase sensitive detector
1 Blanking and back-off
Ion pump control unit.
Bake out control unit
Phase shift.
Filter and oscillator.
Beam modulation.
Power amplifier.
Pulse width delay.
Clock generator.
Power unit
Ion pump control unit.
Temperature control unit for specimen stages.
Power unit for heating stages
0 → 10 Amp at 0 → 30 Volts

FIGURE 6



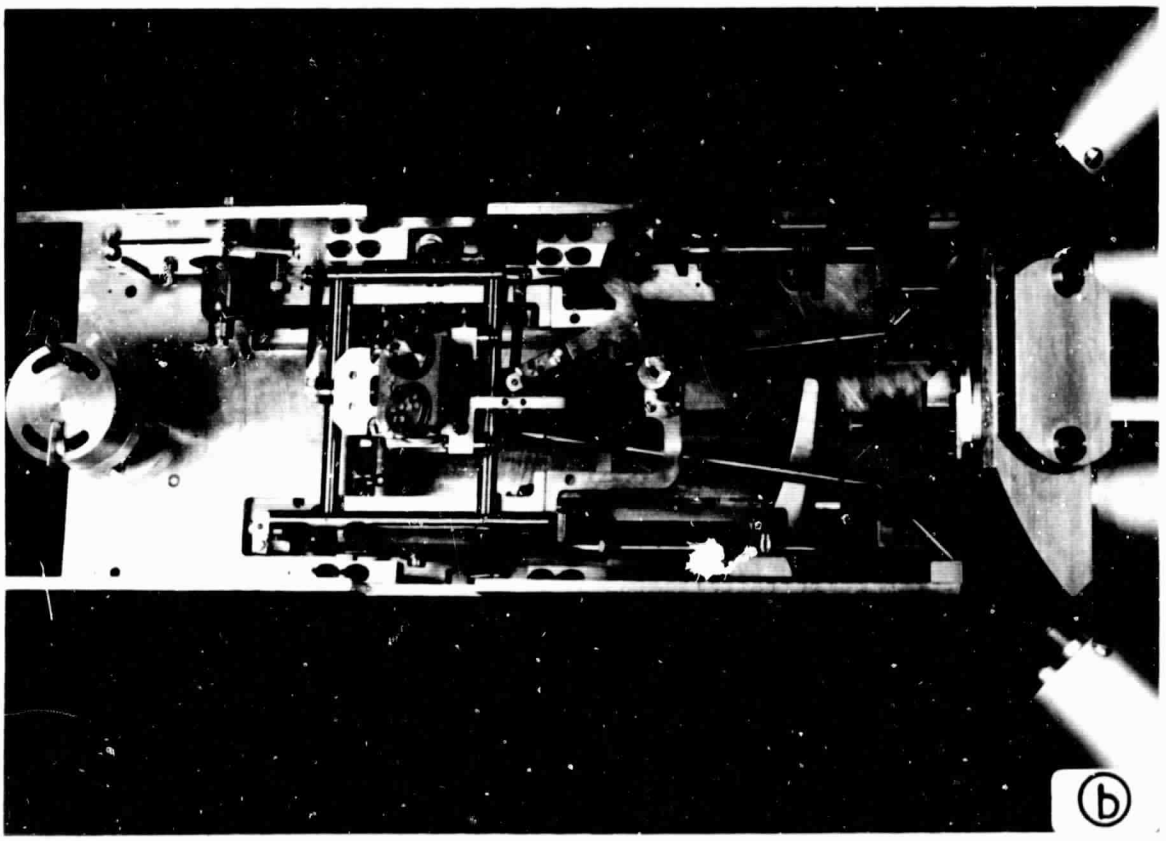


FIGURE. 7.

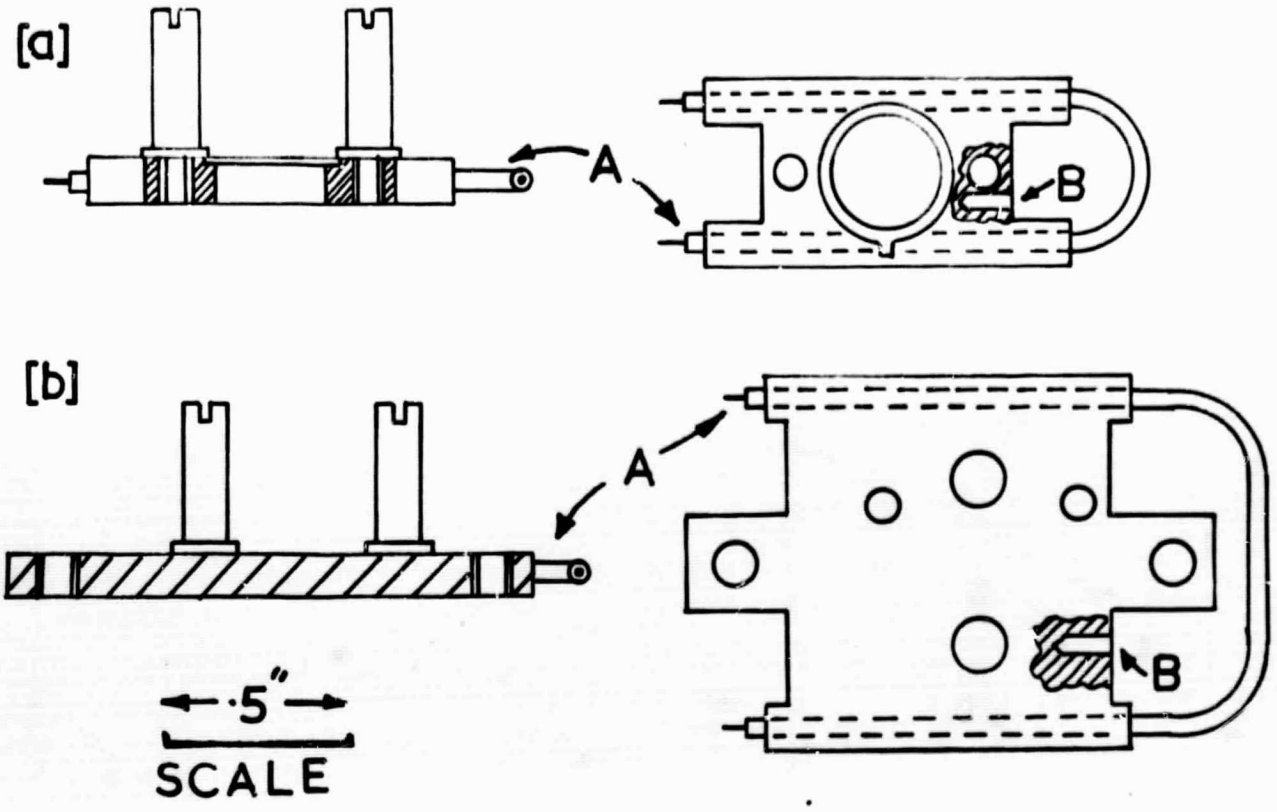


FIGURE 8a

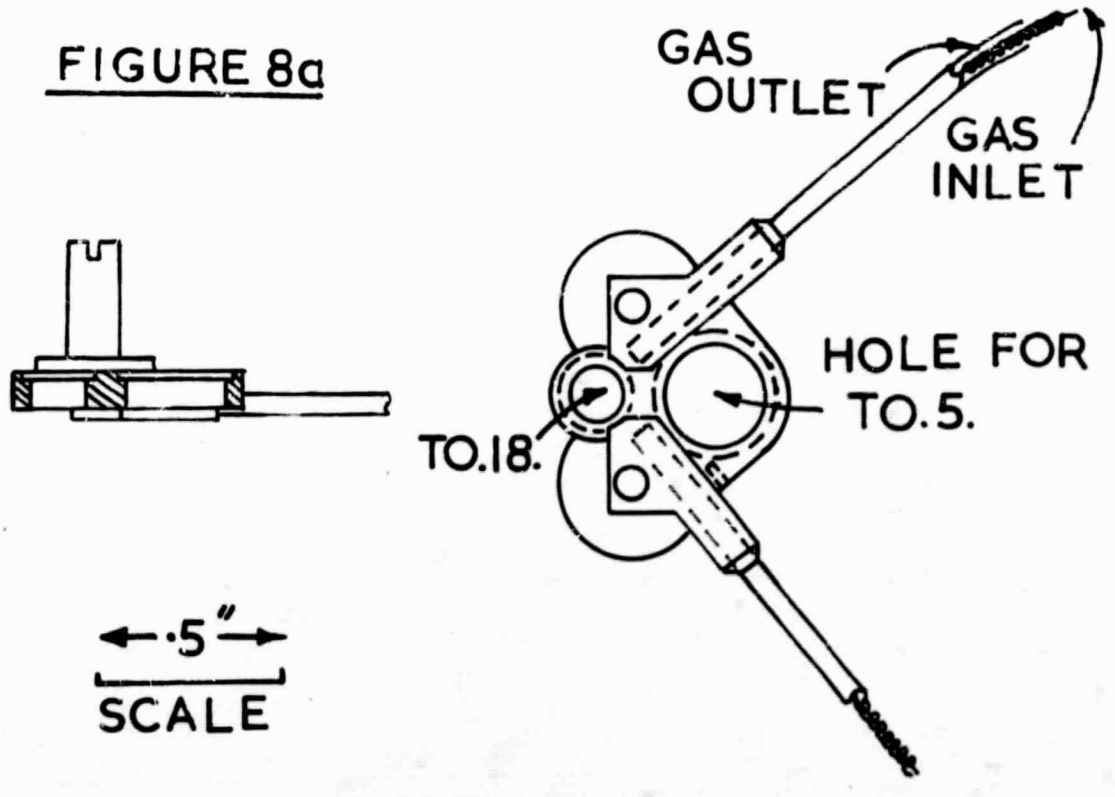


FIGURE. 8 b.

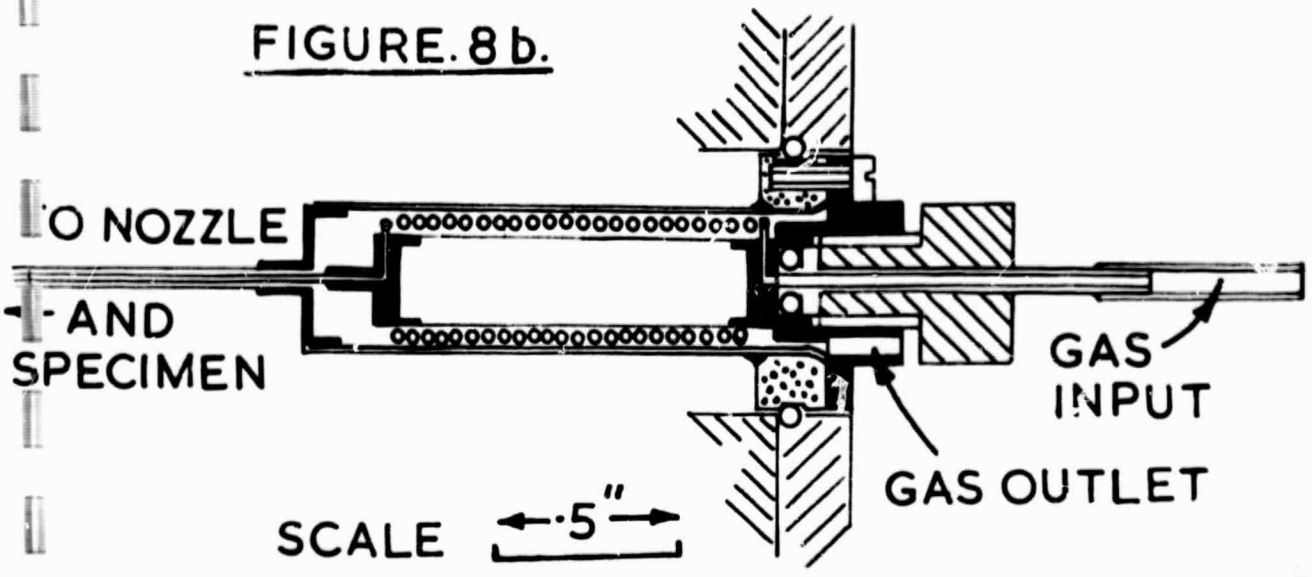


FIGURE. 9.

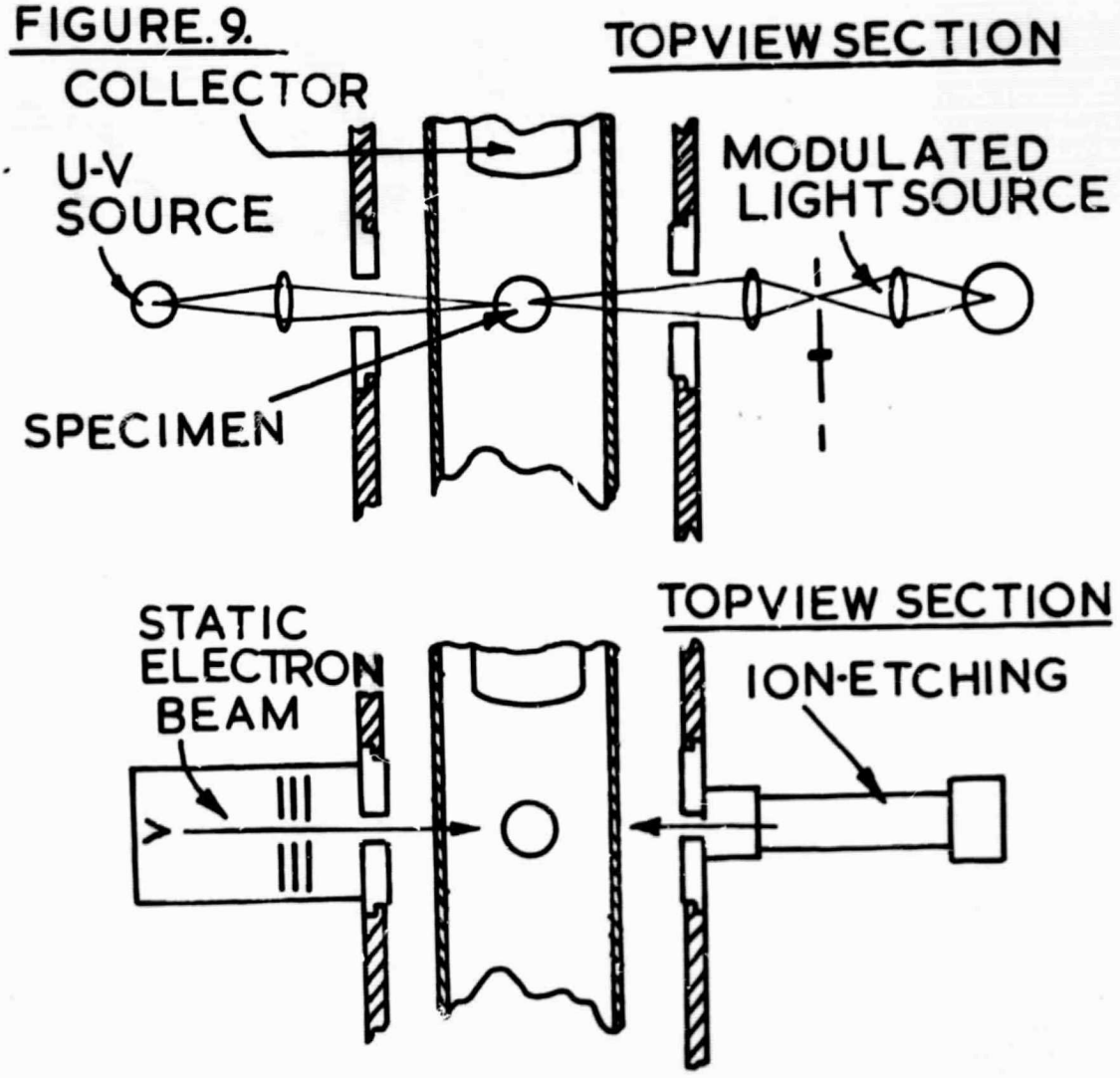


FIGURE 8c

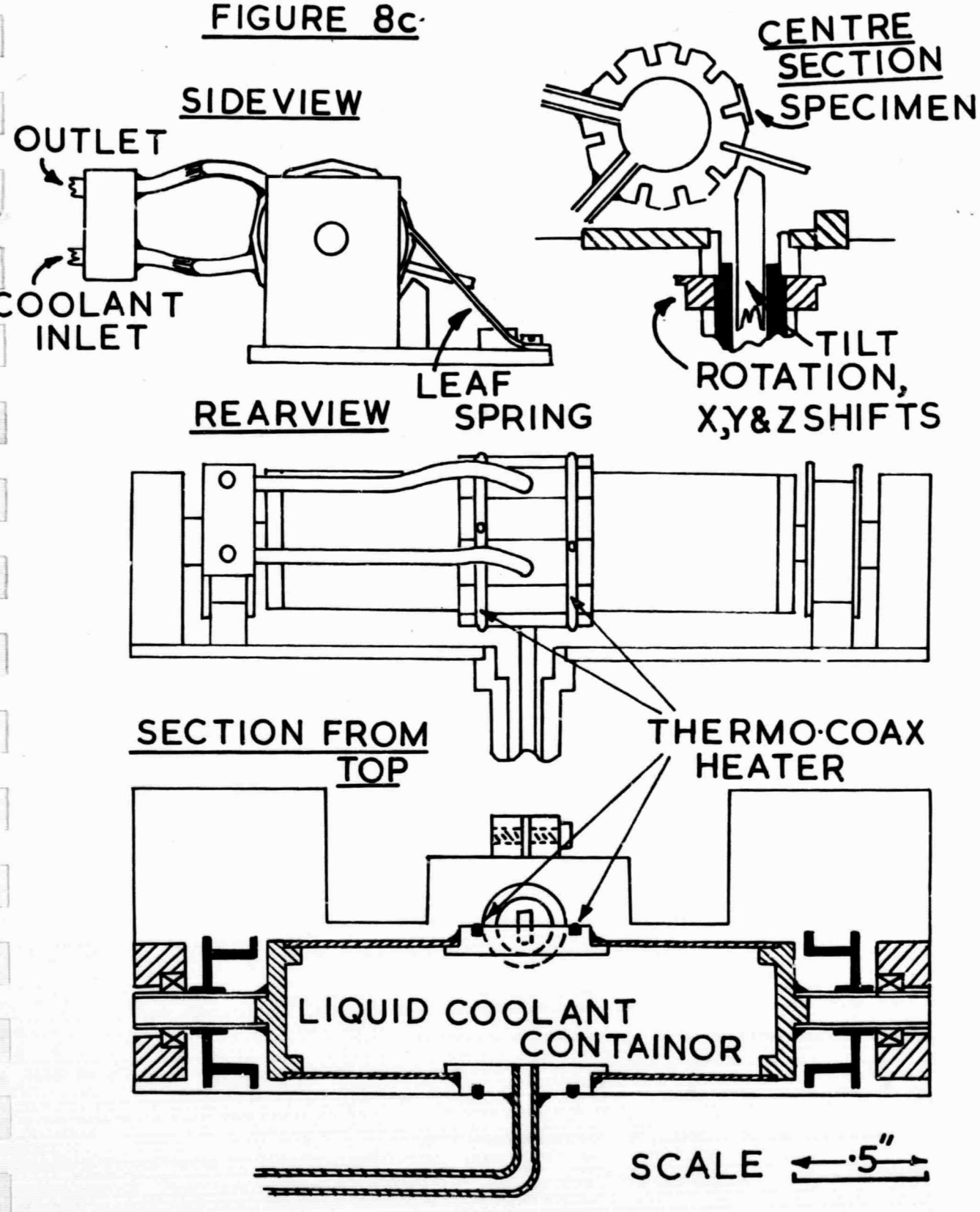
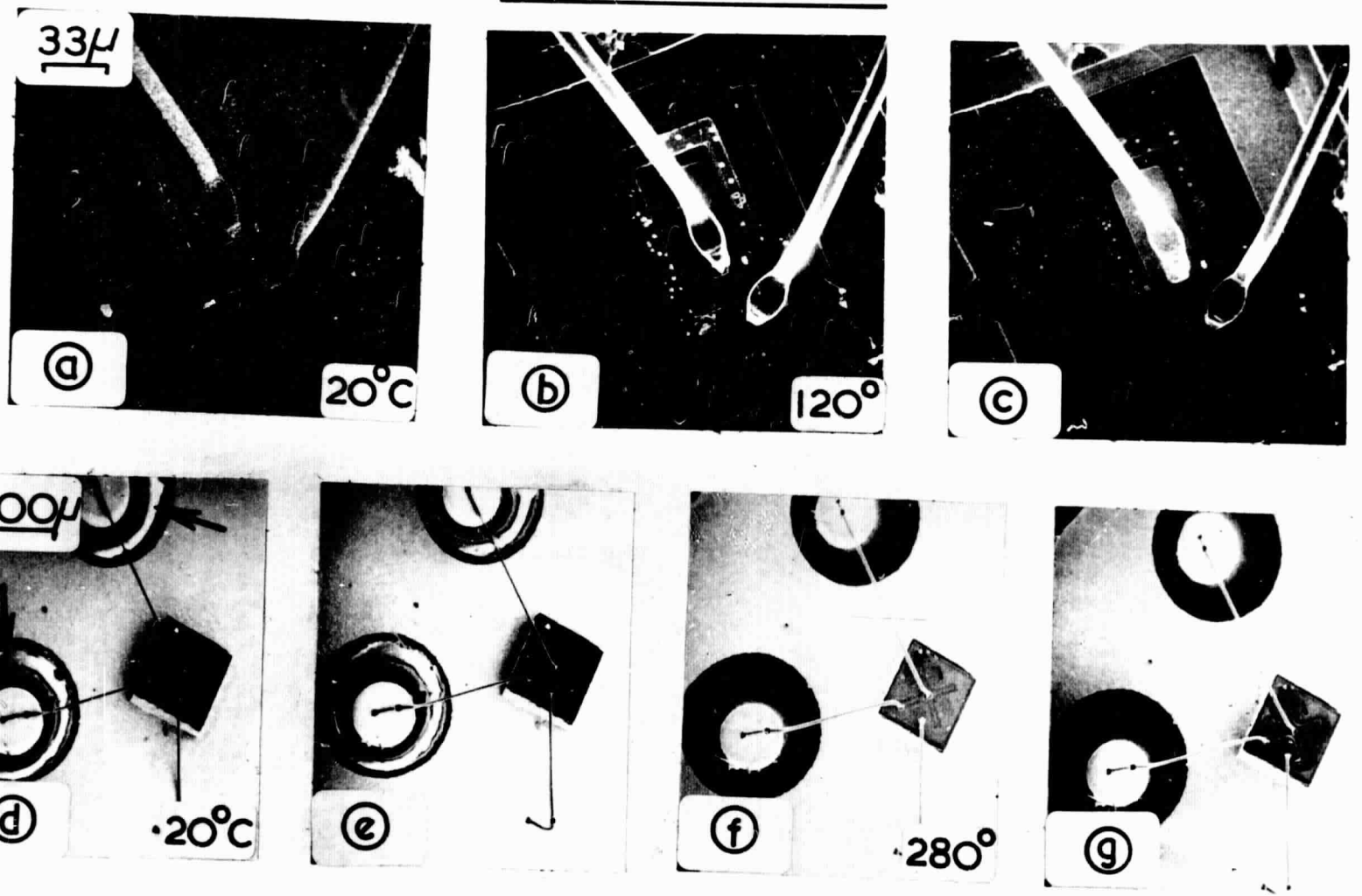

SIDEVIEW
OUTLET
COOLANT INLET
LEAF SPRING
CENTRE SECTION SPECIMEN
TILT
ROTATION, X,Y&Z SHIFTS
REARVIEW
SECTION FROM TOP
THERMO-COAX HEATER
LIQUID COOLANT CONTAINOR
SCALE ·5"

FIGURE 10



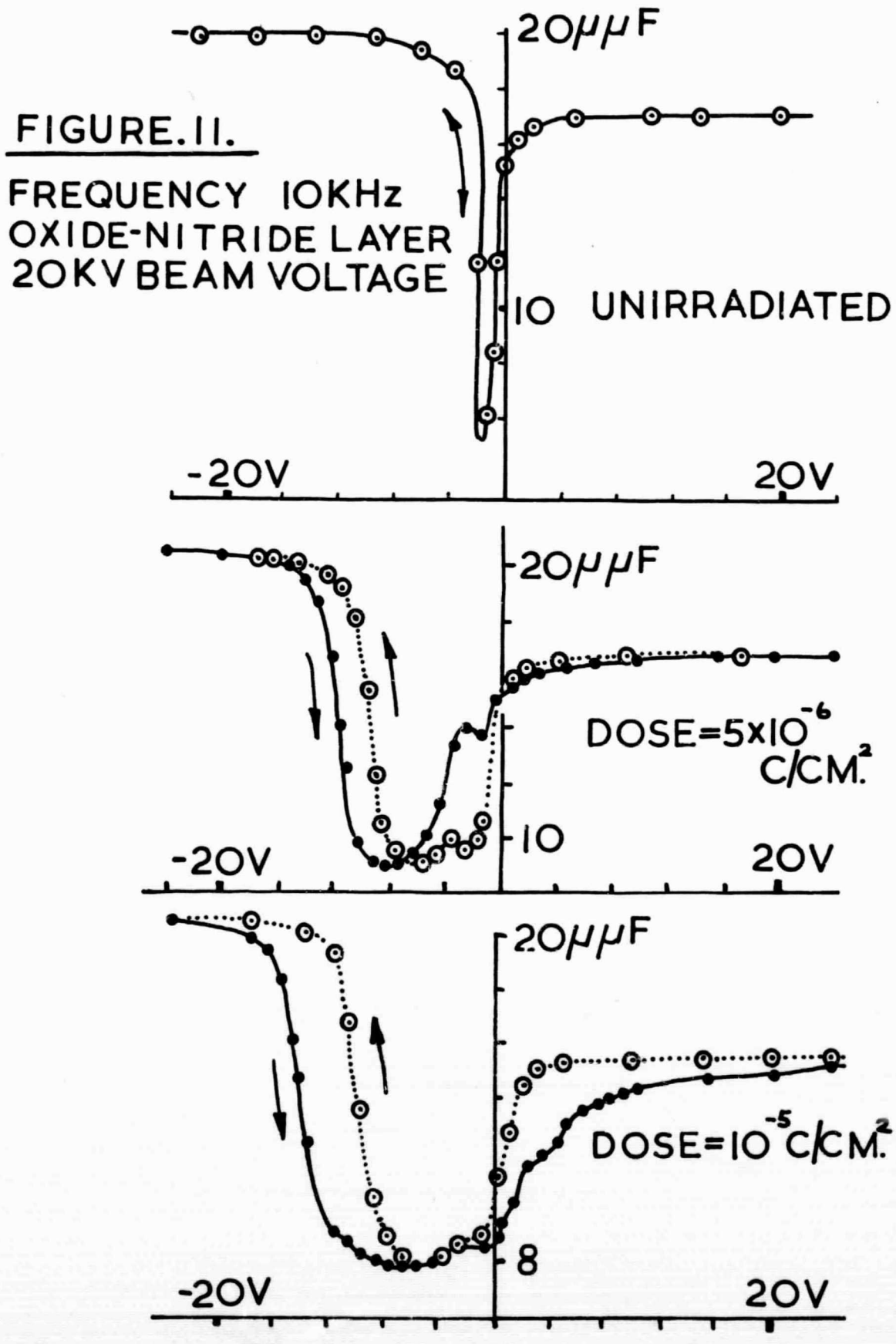
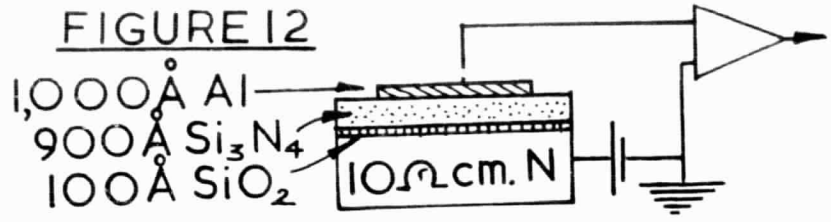


FIGURE.11.

FREQUENCY 10KHz
OXIDE-NITRIDE LAYER
20KV BEAM VOLTAGE

FIGURE 12



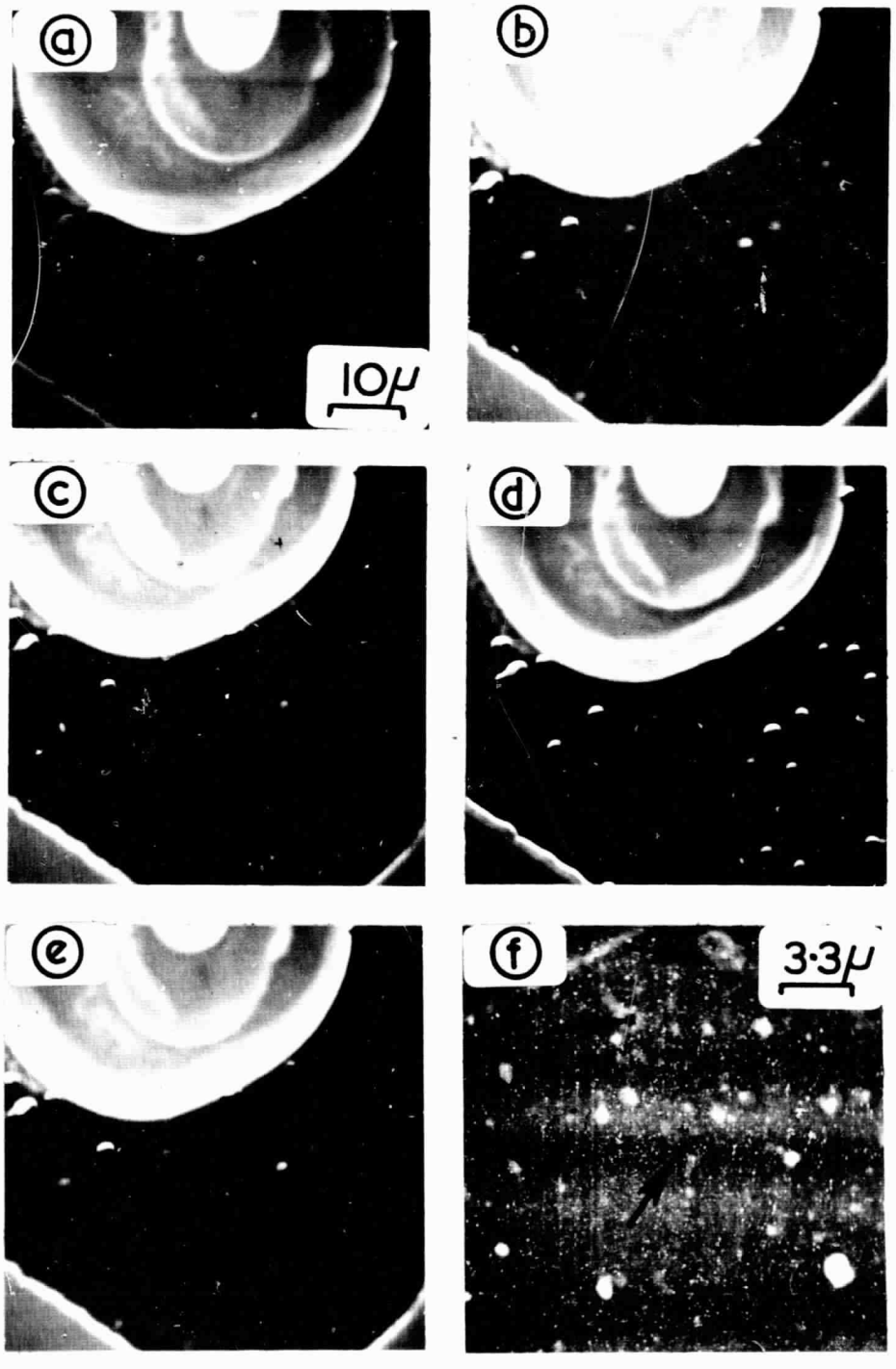


FIGURE.13.

MIS DEVICE, 1,000Å Al, 900Å Si_3N_4, 10Ω cm., N-TYPE Si, 5KV.